FAST & ACCURATE PREDICTION OF ANTENNA-SPACECRAFT MULTIPATH EFFECTS

Final Report

JPL Task 1015

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A. OBJECTIVE

In recent years, spacecraft-antenna design has been a process often requiring many expensive iterations before an acceptable design is obtained. At present, predictions of the combined antenna-spacecraft multipath performance are quite limited and a mockup of the vehicle with the antenna must be built and tested. In the future, fast and efficient computational modeling of antenna-spacecraft electromagnetic (EM) performance must play a larger role in the antenna-design process, and these cut-and-try methods must be used less.

The objective of this research project was to develop a new, fast and accurate EM solver [1] of UHF antenna-spacecraft performance (multipath) that significantly reduces the time and memory (e.g., 100 to 1000 times faster and 100 to 1000 times less memory) required to create and iterate an all-metal, antenna-spacecraft design.

In our approach, we strived to develop an accurate and efficient EM solver of surface integrals based on the Magnetic Field Integral Equation (MFIE) as well as the corresponding Electric Field Integral Equation (EFIE), and their combination [2]. In attempting to develop accurate and efficient integrators for these surface integrals, two main problems were addressed, namely, accurate evaluation of the singular *adjacent interactions* without undue compromise of speed, and fast evaluation of the voluminous number of *nonadjacent interactions* without compromise in accuracy.

Our adjacent, high-order integrators are based on *analytical resolution of singularities*. The only alternative approach in existence is based on strategies of refinement around singularities (Canino et al. [3]). The approach we introduce is advantageous since it does not require costly setup manipulations, and it leads to substantially more accurate and faster numerics.

The accelerator we introduced for the *nonadjacent interactions*, in turn, is related to one of the most advanced FFT (fast Fourier transform) methods developed recently [4]. A number of innovations in our approach, however, lead to very significant memory savings and faster numerics. Our design reduces, significantly, the size of the required FFTs – from N^2 to $N^{4/3}$ points, with proportional improvement in storage requirements and operation count. Further, it results in super-algebraic convergence of the equivalent source approximations *as the electrical size of the body (spacecraft) is increased*.

B. PROGRESS & RESULTS

1. EM Field Solver Results for Metallic Bodies

We computed results for well-known and widely used test geometries with surface singularities (edges, tips); cube, lenticular body of revolution, and ogive. For our new non-accelerated Maxwell solver, scattering results for an electromagnetic cube (Fig. 1) of about one wavelength on diagonal were obtained with errors of the order of 10^{-4}, while results for the electromagnetic lenticular body of revolution (Fig. 2) two wavelengths in diameter were obtained with errors 10^{-5}. Comparison of results with and without our fully accelerated Maxwell solver for an ogive (Fig. 3) are summarized in Table 1.

2. EM Field Solver Results for Large Penetrable Bodies

We illustrate the capabilities of this method by means of two-dimensional scattering by a dielectric tube with refractive index distribution, depicted in Figure 4. In Table 2, the numerical results for this example demonstrate both the O(N logN) complexity and the high-order convergence rate of our method. In particular, the method seems to yield significantly more than second-order convergence in the near field and third-order convergence in the far field for discontinuous scatterers.

3. Geometry Representation Results

Generally, the raw geometry representations available in engineering practice must be processed to satisfy the requirements of a given EM solver. As an example of the geometry processing that might be required, consider the moon-lander spacecraft shown in Figure 5. Use of an accurate high-order integral equation (IE) solver in connection with a geometry of this type requires highly accurate parameterizations of the surface, which can only be produced through partition of the geometry in appropriately simple sub-domains followed by appropriate sub-domain parameterization. The processing steps we used may be classified into 1) Patching, and 2) Smooth-patch representation.

<u>Patch detection</u> - One type of sub-domain that can be treated easily is a planar surface. Vehicles such as those shown in Figure 5 often have many planar regions, and in such regions the re-parameterization required for a given IE solver can be performed quite easily on a mesh for which the necessary re-parameterization is straightforward. The main problem associated with planar regions is detection. Rather than have the user explicitly mark regions that are planar, such simple patches are automatically detected and processed. Smooth, non-planar patches are numerous as well. The problem of parameterization of such patches are complex and require user interaction for correct processing. For example, when we find a single patch that contains both planar and non-planar elements, the user must specify how such a patch is handled.

Smooth-patch representation – For singularities arising from intersection of smooth, non-planar surfaces, we provide smooth representations of surfaces whose triangulations are abruptly terminated at an edge, although the original surface could be continued smoothly just like each face of a cube can be continued smoothly, beyond its edges and corners, as a larger planar surface. We generate parameterizations in this case by means of Fourier series expansions of a smooth periodic function with period larger than the domain in which the data is given. The Fourier series interpolator is likely to be highly oscillatory, but with added conditions we can ensure that, in some appropriate sense, they decay "fast enough" for the smooth function they interpolate. This can be accomplished by requiring that these coefficients be multiplied by certain growing factors that vanish in the least-square sense. The factors equal one for low-order coefficients, and various rates of growth, from polynomial to exponential, can be used for higher-order modes [5].

4. Comparison with other "Fast" solvers

In the following, we compare our results with the some of the most competitive algorithms available. We compare the overall performance of our method with the Fast Multipole Method [6] FMM-based algorithm called "FISC" [7], we compare our Nystrom high-order integrator to that of "FastScat" [3], and we outline the distinctions between our approach and the AIM [4] algorithm.

The FMM-based algorithms provide considerable acceleration; they run in as little as O(N logN) operations per iteration. However, high-order accuracy has not been demonstrated in FMM computations of wave scattering. A possible explanation for this fact is that the FMM approach contains multiplication by Hankel functions of high order. These operations lead to accuracy limitations known as "subwavelength breakdown." In contrast, the FFT acceleration techniques are stable. Table 3 compares the performance of our algorithms to FISC and we see that the present algorithm achieves considerably higher accuracy with less computational resources.

In Table 4, we present results from our basic high-order integrator without use of FFT acceleration, together with results produced by the program FastScat, which utilizes the high-order Nystrom discretization technique proposed in [3], for scattering by a small sphere. We only show setup time reported in [3], since LU decomposition was used to solve their resulting linear system. Our algorithm shows the full time required for the setup and solution. It should be noted that different computers were used (Sparc 10 in [3] and a 400MHz PC in our work) and different problems were solved (Maxwell system in [3] and Helmholtz equation in our work). We see that our method produces substantially more accurate results and smaller computing times.

In comparison with AIM [4], our FFT acceleration technique differs in that it uses surface rather than volumetric distributions of equivalent sources which lead to 1) substantially reduced memory requirement, 2) spectrally convergent approximations, and 3) improved operation count. For example, for an N point discretization, AIM requires an $O(N^{3/2})$ FFT and a corresponding $O(N^{3/2})$ amount of RAM. Our method requires six

FFTs of $O(N^{4/3})$. This implies a significantly lower memory requirement. Such reductions and convergence properties have allowed us to compute very accurately, on a personal computer, scattering from the bodies of sizes close to the largest reported up to now [4], where forty IBM SP2 nodes were used in the latter work to treat scatterers of diameters up to 70λ; no error estimates were given in that work.

C. SIGNIFICANCE OF RESULTS

We succeeded in developing an initial research code to verify this new, fast and accurate solver technique that performs substantially better (faster & with less memory) than current conventional methods. This improvement was demonstrated by testing the new algorithm's performance on certain structures with metallic & dielectric properties. This result is a first step toward developing a fully validated EM simulation for predicting with full fidelity the near-fields and far-fields of complete antenna/spacecraft/solar panel structures. We expect this work to lead to reduction in cost of spacecraft design, enhanced performance of the spacecraft telecom link, and improved performance of certain on-board scientific-instrument-antenna systems.

D. FINANCIAL STATUS

The total funding for this task was $100,000, all of which has been expended.

E. PERSONNEL

Besides Dr. Vaughn Cable and Professor Oscar Bruno, other personnel involved were Caltech post docs Drs. Matt Pohlman, Randy Paffenroth, and Christophe Geuzaine.

F. PUBLICATIONS

None.

G. REFERENCES

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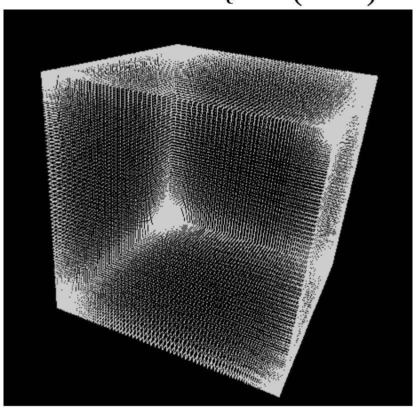

Figure 1. Electromagnetic (conducting) cube with 1λ diagonal.

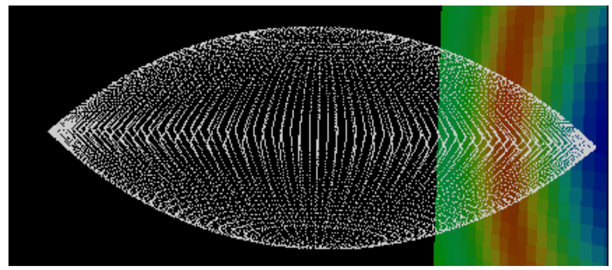

Figure 2. Electromagnetic (conducting) lenticular body of revolution with 2λ.

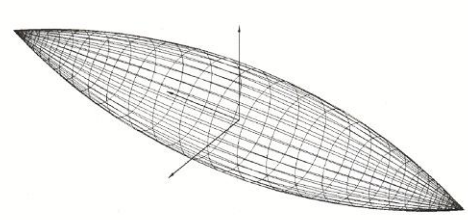

Figure 3. Electromagnetic (conducting) ogive with lengths from 1λ to 20λ.

Figure 4. 2D penetrable scatterer with refractive index n=n(x). Diameter = 10λ.

Figure 5. Sample spacecraft is a complex combination of flat and singular surfaces (edges and tips).

Type	Size	Unknowns	Iterations	Time/Iter	Rel MS Norm	Abs Max Norm
Non-Accel	1λ	1568	20	69s	2.5e-3	1.4e-3
Non-Accel	1λ	6336	17	12m 45s	3.8e-5	2.2e-5
Non-Accel	1λ	25472	17	3h 27m	9.8e-7	4.8e-7
Accelerated	10λ	34112	13	26m	3.8e-4	2.1e-4
Accelerated	20λ	34112	14	14m	6.0e-3	2.4e-3
Accelerated	20λ	72320	19	67m	5.4e-5	2.1e-5

Table 1. Results for conducting ogive with and without our accelerated solver (400 MHz CPU with 1 GB RAM).

N	Memory	Iter	Time	NF Error	Ratio	FF Error	Ratio
12K	19 MB	54	36s	2.2e-5		7.3e-9	
25K	39 MB	54	72s	4.8e-7	44.9	1.1e-11	692
50K	75 MB	54	160s	1.1e-8	45.8	4.5e-12	conv
99K	150 MB	54	331s	4.8e-10	22.1	4.5e-12	conv
198K	305 MB	54	561s	1.4e-11	35.0	4.6e-12	conv
396K	609 MB	54	1172s	1.9e-12	conv	4.7e-12	conv

Table 2. Our results for 2D penetrable dielectric tube (Fig. 4) with refractive index n=n(x) and diameter = 10λ. Iter shows number of iterations required by GMRES [8]; NF and FF errors are absolute maximum norm of error in near- and far-fields; Ratio is ratio of 2 consecutive NF and FF errors.

Algorithm	Sphere Radius	Time	RAM	Unknowns	RMS Error	Computer
FISC	12λ	12h	1.8 GB	602 K	7.2%	SGI R8000
Non-Accel	12λ	6.5h	24 MB	26.2 K	.22%	400 MHz PC
Accelerated	12λ	16h	120 MB	87.3 K	.00096%	400 MHz PC
FISC	24λ	8 x 5h	5 GB	2.4 M	7.9%	SGI Origin (8 cpu)
Accelerated	24λ	33h	807 MB	350 K	.024%	400 MHz PC

Table 3. Results for scattering by large conducting spheres computed using FISC versus our algorithms.

Algorithm	Sphere Radius	Time	Unknowns	RMS Error
Nystrom	2.7λ	1953s (setup)	5400	2.3%
Galerkin	2.7λ	38803s (setup)	5400	.48%
Non-Accelerated	2.7λ	294s	2526	.068%
Non-Accelerated	2.7λ	1430s	5430	.0025%

Table 4. Results for scattering by small conducting sphere using FastScat versus our unaccelerated algorithm.